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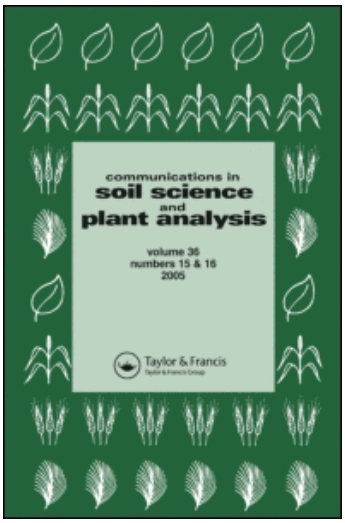

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Estimating soil phosphorus sorption saturation from Mehlich-3 data

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ESTIMATING SOIL PHOSPHORUS SORPTION SATURATION FROM MEHLICH-3 DATA

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ABSTRACT

Soil phosphorus sorption saturation (P_{sat}) measures the degree to which soil phosphorus (P) sorption sites have been filled and has been found to be a good indicator of P availability to runoff and leachate. At present, analytical methods required to estimate P_{sat} are generally not offered by soil testing laboratories. This study evaluated the use of Mehlich-3 data in estimating P_{sat} in a wide range of soils. In acidic soils (pH = 4.1–5.9), P_{sat} estimated from Mehlich-3 P, iron (Fe), and aluminum (Al) was highly correlated with P_{sat} estimated from ammonium oxalate data ($r = 0.94$) as well as with a reference P_{sat} estimated from bicarbonate P and the Langmuir sorption maximum ($r = 0.89$). In alkaline soils (pH = 7.3–8.4), P_{sat} estimated with Mehlich-3 P and calcium (Ca) was highly correlated with the reference P_{sat} ($r = 0.84$), and the strength of that correlation improved only slightly by factoring in soil clay content ($r = 0.86$). Results indicate that P_{sat} may be

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effectively estimated from Mehlich-3 data across a wide range of soils. This study confirms that P_{sat} may be readily estimated by soil testing laboratories that routinely measure Mehlich-3 P, Al, Fe, and Ca.

INTRODUCTION

The sorption of phosphorus (P) by soil plays an important role in the fate of P added to soil from mineral fertilizers and manures (1,2), and, hence, the availability of soil P to plants and water (3,4). Phosphorus sorption saturation provides insight into a soil's ability to release P to solution as well as its remaining capacity to bind added P (5,6) and is defined as follows:

$$P_{sat} = \frac{\text{Sorbed P}}{\text{P sorption capacity}} \quad (1)$$

The components of the P_{sat} equation (sorbed P and P sorption capacity) have been represented using a variety of variables. In acidic soils, amorphous Fe and Al compounds dominate P sorption reactions (7). In these soils, the most common measure of P_{sat} employs P, Fe, and Al extracted by acid ammonium oxalate in the dark (referred to as "oxalate extraction" in this paper) (5). These elements are related in the equation:

$$P_{sat} = \frac{P_{ox}}{\alpha(Fe_{ox} + Al_{ox})} \quad (2)$$

where P_{ox} is oxalate extractable P, Fe_{ox} is oxalate extractable Fe, Al_{ox} is oxalate extractable Al and α represents the proportion of Fe_{ox} and Al_{ox} dedicated to P sorption (8). Oxalate extractable P_{sat} has not been applied to calcareous soils, where Ca dominates P sorption reactions, as oxalic acid precipitates Ca during oxalate extraction and reacts with carbonate to change the pH of the acid buffer (9).

Other approaches to estimating P_{sat} that have wider applicability than the oxalate approach relate some measure of sorbed P, often soil test P, to indicators of P sorption capacity such as the Langmuir adsorption maximum (S_{max}), or the single point P Sorption Index (PSI). Both S_{max} and PSI are strongly correlated (10) and provide estimates of "effective P sorption capacity" or "remaining P sorption capacity" (11,12). For instance, Sallade and Sims (13) related 0.1 *M* NaOH P to PSI to estimate P_{sat}, which they found highly correlated with soluble P concentrations in anoxic sediments.

Soil P sorption saturation is increasingly seen as an environmental indicator for soil P, based upon the observation that more P is released from

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soil to surface runoff or leaching water as P_{sat} increases (6). In the Netherlands, P_{sat}, as determined in Eq. (2) with $\alpha = 0.5$, is used to assess the potential for P leaching to shallow ground water (5). A P_{sat} value of 25% has been established for Dutch soils as the threshold above which the potential for P movement in ground water becomes unacceptable (5). For surface runoff, Sharpley (14) found the concentration of dissolved P in runoff from nine acidic and one calcareous soil to be more closely related to P_{sat} ($r^2 = 0.86$) than Mehlich-3 extractable soil P ($r^2 = 0.28$). He concluded that P_{sat} may represent a more reliable and universal indicator of P loss potential that soil test P alone, with a single regression equation between P_{sat} and runoff P applying to all the soils in the study. In that study, P_{sat} was determined as the ratio of Mehlich-3 extractable P to S_{max}.

The widespread application of P_{sat} in environmental soil testing is hampered by a paucity of data required to estimate P_{sat} as well as the inherent limitations of certain analyses. Most analyses required to estimate P_{sat} (e.g., oxalate extraction, NaOH extraction, P sorption isotherms, PSI) are not offered by soil testing laboratories. Many of these methods are too time consuming or difficult to conduct to be widely adopted by commercial soil testing laboratories (15). Furthermore, soil-specific limitations to certain analyses prevent their use on the wide range of soils that many soil testing laboratories must analyze. As described above, acid oxalate extraction, which is widely used in acidic soils, is not appropriate for calcareous soils.

In an effort to identify a method for estimating P_{sat} that can be used by soil testing laboratories, alternative measures of P_{sat} in soils of widely differing mineralogies were examined. To do this, alternative approaches to estimating the P sorption capacity components of the P_{sat} equation were first compared, before ultimately comparing established measures of P_{sat} with empirical measures of P_{sat} derived from Mehlich-3 data.

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MATERIALS AND METHODS

Soils

Surface soil samples (A horizon) were obtained from the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) National Soil Survey Laboratory archives. Tables 1 and 2 list the 37 acidic and 25 alkaline soils used in the study, respectively, as well as select properties, and NRCS identification numbers that can be used to obtain additional information from http://vmhost.cdp.state.ne.us/~nslsoil/PEDON.HTML.

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Table 1. Properties of Acidic Soils Included in Study

					Oxalate-Extractable Elements			Mehlich-3 Extractable Elements					
NRCS ID	Series	Order	pH	Clay (%)	P (mmol kg^{-1})	Al (mmol kg^{-1})	Fe (mmol kg^{-1})	P (mmol kg^{-1})	Al (mmol kg^{-1})	Fe (mmol kg^{-1})	Ca (mmol kg^{-1})	Bicarb P (mmol kg^{-1})	S_{max} (mmol kg^{-1})
78P2249	Craven	Ultisol	4.1	7	0.7	19.9	14.5	0.4	25.9	2.3	1.2	0.1	10.7
79P0002	Cheat	Inceptisol	4.1	38	16.3	86.9	75.2	2.6	41.8	2.3	13.6	0.6	26.9
81P0186	Doniphan	Ultisol	4.2	10	1.5	19.8	17.5	0.8	28.1	7.4	3.2	0.2	13.5
81P3857	White Store	Alfisol	4.2	11	1.2	29.0	20.9	0.6	22.9	3.4	0.7	0.3	16.3
78P1820	Lyman	Spodosol	4.3	10	8.2	215.3	229.6	0.6	44.3	3.0	1.1	0.5	37.8
83P3316	Rains	Ultisol	4.3	9	0.8	46.4	29.4	0.3	27.4	4.2	0.7	0.2	23.4
78P0191	Georgeville	Ultisol	4.4	16	0.5	30.4	34.4	0.3	25.2	4.9	1.6	0.1	16.6
83P2608	Granville	Ultisol	4.4	9	0.0	12.3	7.4	0.1	17.4	1.8	0.6	0.0	12.5
78P0221	Georgeville	Ultisol	4.5	13	0.5	29.5	23.3	0.2	20.8	2.6	0.6	0.2	18.2
78P1804	Lyman	Spodosol	4.6	8	14.2	165.5	197.1	1.1	44.1	3.3	0.9	0.4	30.8
82P1623	Stonveville	Ultisol	4.6	31	2.8	68.1	32.5	0.4	34.7	1.2	2.3	0.2	23.7
78P1811	Berkshire	Spodosol	4.7	8	6.9	128.4	119.4	1.1	37.1	3.2	7.4	0.5	25.5
81P1335	Ruston	Ultisol	4.8	4	0.5	10.1	3.9	0.2	13.4	1.2	1.4	0.6	12.0
78P3383	Pittstown	Inceptisol	4.9	8	12.1	106.4	97.5	0.6	39.8	1.7	4.5	0.3	25.3
	Malbis	Ultisol	4.9	12	1.4	106.3	39.0	0.3	42.5	2.9	6.1	0.1	8.2

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80P2707	Norfolk	Ultisol	4.9	2	7.4	14.5	5.5	5.5	17.9	2.2	3.0	1.6	10.6
80P2188	Lansing	Alfisol	5.0	12	10.7	88.0	122.1	0.4	9.4	1.8	0.8	0.3	22.2
80P665	Sassafras	Ultisol	5.0	7	7.5	30.1	14.4	3.5	23.7	3.1	20.8	0.6	14.4
81P1769	Mardin	Inceptisol	5.1	18	14.7	65.0	85.9	2.1	30.2	3.0	16.3	0.8	17.3
16963	Hosmer	Alfisol	5.2	14	5.5	36.4	31.9	2.5	23.4	3.3	56.6	0.4	14.5
81P1729	Caribou	Spodosol	5.3	14	25.5	138.6	107.6	3.7	46.1	2.2	10.9	1.5	19.8
78P1944	Calloway	Alfisol	5.3	12	1.8	21.8	32.3	0.5	17.2	2.4	11.1	0.2	12.9
78P2915	Madison	Ultisol	5.4	14	2.2	29.9	12.7	0.6	24.5	1.3	7.8	0.4	14.5
81P1755	Hagerstown	Alfisol	5.5	19	8.5	75.4	39.5	0.8	33.0	1.2	16.6	0.1	18.6
78P1931	Loring	Alfisol	5.5	11	1.5	22.0	18.2	0.4	17.5	2.1	23.6	0.1	14.1
80P2961	Russian	Mollisol	5.6	14	7.2	22.7	44.5	0.2	6.6	0.8	132.2	0.3	13.7
80P2382	Crete	Mollisol	5.6	23	8.1	26.3	23.6	2.1	17.4	2.4	29.2	0.7	13.5
761348	Muscatine	Mollisol	5.6	25	10.8	32.9	43.5	2.2	20.7	2.4	50.0	0.4	15.2
78P2897	Raybun	Alfisol	5.6	59	3.7	60.3	31.4	0.4	27.5	0.8	22.4	0.2	22.8
81P4713	Berit	Aridisol	5.6	3	5.5	12.7	5.2	4.0	17.5	2.6	4.8	0.7	12.2
81P2624	Lake	Entisol	5.6	2	5.9	17.2	6.9	4.7	20.9	2.0	4.5	1.1	12.2
77P2586	Holland	Alfisol	5.7	17	20.7	191.9	39.1	3.0	48.4	1.7	13.4	1.0	24.6
16549	Fayette	Alfisol	5.7	15	8.8	23.5	33.8	0.8	23.3	1.4	13.9	0.6	13.2
73L263	Wymore	Mollisol	5.8	31	7.4	39.9	31.2	0.8	17.9	3.8	37.5	0.5	16.4
81P2617	Lakeland	Entisol	5.8	2	11.7	28.0	8.6	8.8	26.8	2.5	6.6	1.4	11.8
20449	Hastings	Mollisol	5.9	23	5.9	24.2	11.0	1.8	26.8	2.2	54.3	0.5	13.0
80P2234	Davidson	Ultisol	5.9	20	4.6	57.3	20.4	0.9	30.5	0.9	12.2	0.4	16.8

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Table 2. Properties of Alkaline Soils Included in Study

					Oxalate-Extractable Elements			Mehlich-3 Extractable Elements					
NRCS ID	Series	Order	pH	Clay (%)	P (mmol kg^{-1})	Al (mmol kg^{-1})	Fe (mmol kg^{-1})	P (mmol kg^{-1})	Al (mmol kg^{-1})	Fe (mmol kg^{-1})	Ca (mmol kg^{-1})	Bicarb P (mmol kg^{-1})	S_{max} (mmol kg^{-1})
80P1952	Witt	Aridisol	7.3	11	4.6	17.5	5.4	2.15	16.5	0.9	45.9	0.8	12.9
81P1596	Payne	Alfisol	7.3	26	2.7	25.1	5.9	0.95	18.8	0.6	71.9	0.4	12.2
80P0531	Ord	Mollisol	7.4	3	0.01	7.4	5.2	0.02	7.8	3.5	11.3	0.0	7.5
81P2830	Kidman	Mollisol	7.5	17	11.3	20.6	17.6	3.09	16.3	1.8	52.6	1.9	13.2
80P1782	Pullman	Mollisol	7.5	32	3.7	29.8	7.1	1.26	22.3	0.7	67.1	0.4	14.5
81P1503	Leeper	Inceptisol	7.6	36	11.6	41.1	45.3	2.49	23.2	2.0	102.2	1.0	16.7
82P2333	Fairpoint	Entisol	7.7	18	3.0	16.2	52.1	0.01	4.0	2.0	118.7	0.1	17.9
83P2695	Lakoma	Inceptisol	7.7	45	14.1	38.0	8.9	0.75	14.4	0.5	427.4	0.5	24.0
80P2273	Bearpaw	Mollisol	7.7	41	7.1	35.7	18.9	1.48	25.3	1.6	48.8	0.5	16.2
17597	Joplin	Mollisol	7.7	22	4.0	21.2	10.8	0.87	13.8	0.7	67.4	0.4	13.8
80P2758	Baknoll	Mollisol	7.9	25	6.8	13.1	38.8	0.36	0.1	0.2	735.2	0.3	26.1
80P0594	Crofton	Entisol	8.0	23	8.0	19.2	12.6	1.48	19.7	1.5	48.3	0.2	14.5
81P2040	Glenbar	Entisol	8.1	43	28.7	38.0	18.0	0.53	11.8	0.9	252.9	0.3	24.6
81P3447	Billings	Entisol	8.1	26	9.8	10.0	25.0	0.01	0.2	1.2	140.6	0.1	19.2
81P3578	Frio	Mollisol	8.1	39	5.5	27.5	4.2	0.17	7.7	0.4	327.2	0.1	27.6
82P3913	Thiokol	Aridisol	8.1	22	7.8	13.3	14.2	0.01	0.3	0.4	430.7	0.1	19.7
81P0524	Topsey	Mollisol	8.2	40	0.2	9.2	2.6	0.02	0.0	0.4	834.9	0.0	24.6
76P0315	Sanpete	Aridisol	8.2	18	3.6	14.1	4.2	0.90	0.7	0.1	516.5	0.3	19.7
81P1976	Indio	Entisol	8.3	16	6.3	7.2	10.5	0.95	0.1	0.9	187.1	0.4	11.5
82P2670	Jordan	Alfisol	8.3	32	11.4	11.7	8.0	0.13	0.1	0.2	737.9	0.1	36.6
81P2815	Millville	Mollisol	8.3	13	11.1	26.7	13.2	1.38	9.5	0.9	111.0	0.4	14.8
81P1876	Amarillo	Alfisol	8.3	9	0.7	8.7	2.1	0.37	9.6	0.4	28.0	0.1	12.8
81P1589	Bosque	Mollisol	8.3	30	8.2	32.3	7.6	1.65	7.6	0.4	205.3	0.5	14.9
81P1582	Venus	Mollisol	8.3	10	1.9	12.7	2.2	0.56	3.6	0.2	104.8	0.1	12.9
81P0092	Avondale	Entisol	8.4	21	18.7	22.6	7.2	1.83	3.7	0.5	134.5	0.3	15.2

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Soil Extraction and Analysis

Air-dried soils (< 2 mm) were subject to Mehlich-3 (16), Olsen (17), and oxalate extraction (18). Mehlich-3 extraction was conducted by shaking 2.5 g of soil in 25 mL of Mehlich-3 solution (0.2 *N* CH_3COOH + 0.25 *N* NH_4NO_3 + 0.015 *N* NH_4F + 0.013 *N* HNO_3 + 0.001 *M* EDTA) for 5 min; bicarbonate (bicarb) extraction by shaking 1 gram of soil in 20 mL of 0.5 *M* $NaHCO_3$ (pH 8.5) for 30 min; and oxalate extraction by shaking 0.25 g of soil in 10 mL of acid oxalate solution (0.1 *M* $(NH_4)_2C_2O_4{\cdot}H_2O$ + 0.1 *M* $H_2C_2O_4{\cdot}2H_2O$) for 4 h in the dark. Mehlich-3 and bicarb extracts were filtered through Whatman #1 paper, while oxalate extracts were first centrifuged (510*g* for 20 min) and then filtered (0.45 μm). Bicarb P was determined by the method of Murphy and Riley (19). Mehlich-3 and oxalate extractable P, Ca, Fe, and Al concentrations were determined by ICP. All extractions were conducted in duplicate.

Phosphorus sorption isotherms were determined by the method of Nair et al. (20). Standard P solutions, from 0–300 mg PL^{-1}, were obtained by dissolving KH_2PO_4 in 0.01 *M* $CaCl_2$. Duplicate sub-samples, weighing 5.0 g, were shaken for 24 h in 20 mL of standard solution (soil : solution = 1 : 4), allowed to settle overnight, and then filtered through Whatman #42 paper. Filtrate P concentrations were determined colorimetrically by the method of Murphy and Riley (19).

Phosphorus sorption isotherms were described with the linear form of the Langmuir equation, from which S_{max} was calculated. By plotting C/S against C, where C is solution P concentration and S is sorbed P concentration, S_{max} was determined as the reciprocal of the slope of the linear regression (21,22).

Particle size analysis was conducted by the pipette method (23), and soil pH determined in water (soil : water = 1 : 1).

Calculation of P_{sat}

In all cases, molar concentrations of extracted elements (mmol kg^{-1}) were used to determine P_{sat}. The following definition of P_{sat} was chosen as a reference for all soils in the study:

$$\text{reference } P_{sat} = \frac{\text{bicarb P}}{S_{max} + \text{bicarb P}} \tag{3}$$

Because S_{max} and bicarb P are determined by methods that can be applied to both acidic and alkaline soils, we reasoned that this measure of P_{sat} should serve as the standard for comparison. Specifically, just as oxalate extraction is not appropriate for calcareous soils, Mehlich-3 extraction may not be suitable for calcareous soils because soluble P may be precipitated by CaF_2, a product of the reaction between NH_4F and $CaCO_3$ (24).

Empirical estimates of P_{sat} are calculated by approximating sorbed P and P sorption capacity (Eq. (1)) for acidic (pH $<$ 7.0) and alkaline (pH $>$ 7.0) soils. Notably, in estimating P_{sat} from oxalate data, this study does not include α. The coefficient α is intended to account for the proportion of Fe_{ox} and Al_{ox} dedicated to P sorption, such that P sorption capacity is not overestimated by these variables. Use of α in the literature, however, has been varied, ranging from its actual measurement (8,25), to the use of assumed α values (26–28), to the exclusion of α from the P_{sat} equation (29,30). Assumed α values, often 0.5 to allow direct comparison with Dutch regulatory data, are obviously arbitrary, given soil specific variations in sorption mechanisms affecting P sorption capacity as well as variability in methods used to estimate the long-term sorption maximum (30,31). Indeed, Schoumans et al. (32) reported an α of 0.3 for sandy Dutch soils, illustrating substantial deviation from the "average" α of 0.5 often cited in the literature for such soils. Given the diversity of soils included in this study, presumably with multiple α, we do not employ α in estimating P_{sat}.

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Statistical Analysis

Associations between extracts were assessed by Pearson's correlation analysis and modeled by least squares regression (33). Best-fitting single and multivariate regressions were determined by best subsets regression using Minitab's statistical software, Release 11 (34).

RESULTS AND DISCUSSION

Estimating Components of P_{sat}: Sorbed Phosphorus and Phosphorus Sorption Capacity

As a first step, we compared the measures of sorbed P (bicarb P, P_{ox}, P_{M3}), to assess the strength of their associations outside of the P_{sat} equation. In acidic soils (Table 1), bicarb P and P_{M3} were strongly correlated ($r = 0.85$, bicarb $P = 0.18P_{M3} + 0.21$), while bicarb P and P_{ox} were more poorly correlated ($r = 0.61$), as were P_{M3} and P_{ox} ($r = 0.44$). Given that strong correlations between these variables have been reported elsewhere for acidic soils (35,36), the most likely reason for the weak correlations observed here is the wide variety of soil mineralogies and textures included in this study. Restricting the analyses to soils with less varied properties may well improve such correlations.

In alkaline soils (Table 2), bicarb P and P_{M3} were again strongly associated ($r = 0.86$, bicarb $P = 0.39\ P_{M3} + 0.01$), while bicarb P and P_{ox}, as well as P_{M3} and P_{ox}, remained poorly correlated ($r = 0.24$ for bicarb P and P_{ox}; $r = 0.25$ for

P_{M3} and P_{ox}). The high degree of correlation between bicarb P and P_{M3} in the alkaline soils suggests that Mehlich 3 is an appropriate extract for such soils, and is supported by similar findings in other alkaline soils (36).

In comparing oxalate and Mehlich-3 indicators of P sorption capacity, we related the reference P sorption capacity (defined as S_{max} + bicarb P) to corresponding oxalate and Mehlich-3 data. In acidic soils, Fe_{ox} and Al_{ox} were most highly correlated with P sorption capacity, independently ($r = 0.82$, P sorption capacity $= 0.10\ Fe_{ox} + 13.3$; $r = 0.81$, P sorption capacity $= 0.99\ Al_{ox} + 12.2$) as well as in combination ($r = 0.86$, P sorption capacity $= 0.56\ Fe_{ox} + 0.05Al_{ox} + 12.3$). Regressions developed from Mehlich-3 data explained considerably less of the variability in P sorption capacity of acidic soils than did oxalate data. Mehlich-3 Al exhibited the greatest correlation with P sorption capacity ($r = 0.62$, P sorption capacity $= 0.37Al_{M3} + 7.9$) while Fe_{M3} was not correlated with P sorption capacity ($p = 0.98$).

Oxalate data were poorly correlated with the reference P sorption capacity in alkaline soils ($p = 0.64$ for Al_{ox}; $p = 0.52$ for Fe_{ox}). Although Fe has been implicated in the P sorption reactions of some alkaline soils (37–39), Fe_{M3} and the reference P sorption capacity were poorly correlated ($r = 0.45$). Similarly, Al_{M3} and P sorption capacity were poorly correlated ($r = 0.34$). Mehlich-3 Ca, however, exhibited a strong correlation with P sorption capacity in these soils ($r = 0.81$, P sorption capacity $= 0.02Ca_{M3} + 13.2$), highlighting the importance of Ca in P sorption. Furthermore, multivariate analysis with Ca_{M3} and soil clay content (%) substantially improved the correlation with P sorption capacity ($r = 0.87$, P sorption capacity $= 0.02Ca_{M3} + 0.20$clay $+ 9.2$). Presumably the positive association between P sorption capacity and clay content reflects the importance of a soil's reactive surface area to P sorption.

Estimating P_{sat} from Oxalate and Mehlich-3 Data

To estimate P_{sat} in acidic soils, P_{sat} was determined using Eq. (2) from either oxalate data (P_{ox}, Fe_{ox} and Al_{ox}) or Mehlich-3 data (P_{M3}, Fe_{M3} and Al_{M3}). Figure 1 illustrates associations between the reference P_{sat} (Eq. (3)) and P_{sat} estimated by oxalate and Mehlich-3 data in acidic soils. Both oxalate and Mehlich-3 estimates of P_{sat} were highly correlated with the reference P_{sat}. Furthermore, P_{sat} estimated from oxalate data was highly correlated with P_{sat} estimated from Mehlich-3 data (Fig. 2). Clearly, in acidic soils the use of Mehlich-3 data to estimate P_{sat} is highly justified.

As several authors have developed P_{sat} equations for acidic soils using extractable Al only as a measure of P sorption capacity (see review in reference (31)), we compared P_{sat} estimated with P, Fe, and Al to that estimated with P and Al only, for both oxalate and Mehlich-3 data. The full and abbreviated estimates of P_{sat} were very highly correlated for both oxalate ($r = 0.95$,

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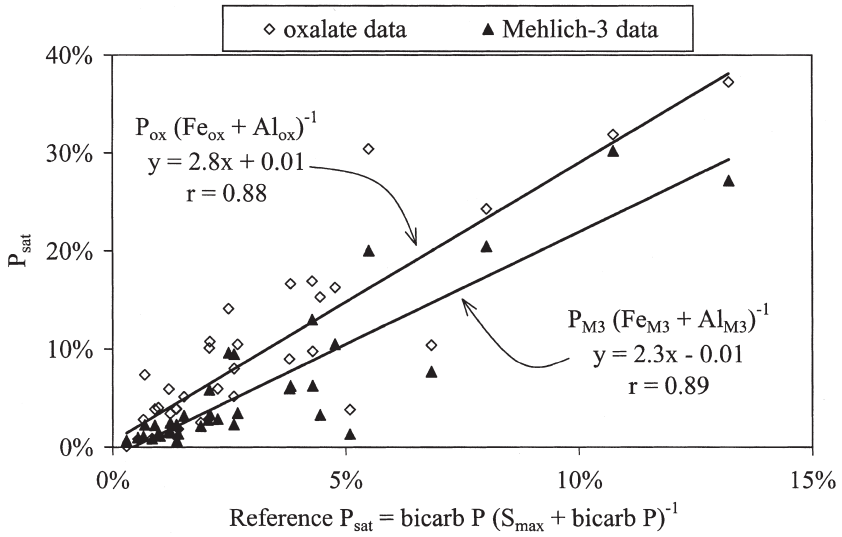

Figure 1. Relationship of reference P_{sat} to P_{sat} estimated from oxalate and Mehlich-3 data in acidic soils.

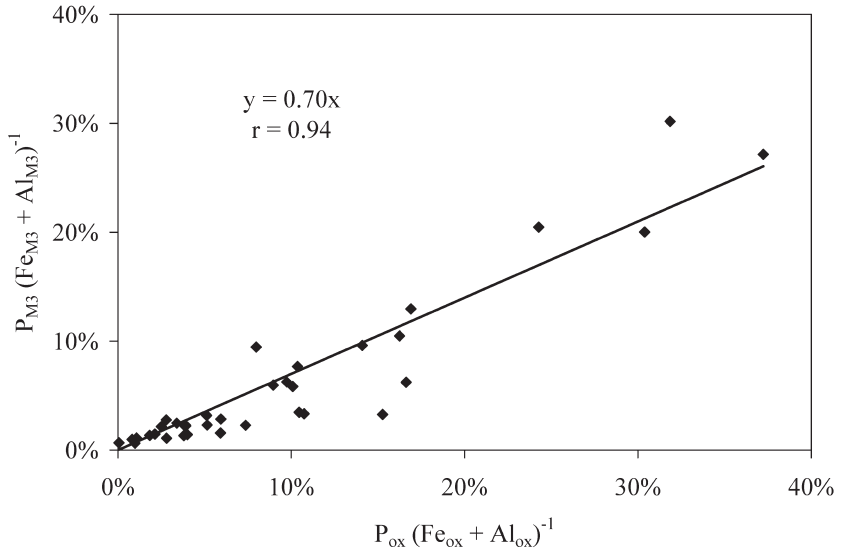

Figure 2. Relationship of P_{sat} estimated from oxalate and Mehlich-3 data in acidic soils.

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$P_{ox}Al_{ox}^{-1} = 1.42P_{ox}(Fe_{ox} + Al_{ox})^{-1} + 0.03)$ and Mehlich-3 data ($r = 0.99$, $P_{M3}Al_{M3}^{-1} = 1.11P_{M3}(Fe_{M3} + Al_{M3})^{-1} - 0.002$). Although Fe certainly contributes to P sorption in acidic soils, as evidenced by the strong association between Fe_{ox} and the P sorption capacity of acidic soils in this study (Table 1), most of the variability in P_{sat} can be explained without extractable Fe. Indeed, these abbreviated measures of P_{sat} were nearly as well correlated with the reference P_{sat} as their counterparts that included Fe ($r = 0.79$, reference $P_{sat} = 0.16P_{ox}Al_{ox}^{-1} + 0.01$; $r = 0.86$, reference $P_{sat} = 0.31P_{M3}Al_{M3}^{-1} - 0.01$). These results support the use of truncated P_{sat} equations in estimating P_{sat} in acidic soils.

To estimate P_{sat} from Mehlich-3 data in alkaline soils, we related P_{M3} to Ca_{M3} alone ($P_{M3}Ca_{M3}^{-1}$), and related P_{M3} to a unitless estimate of P sorption capacity derived from the sum of Ca_{M3} and clay content [$P_{M3}(Ca_{M3} + clay)^{-1}$]. Although textural analyses are generally not conducted as part of standard soil testing procedures, the use of clay content in estimating the P_{sat} of alkaline soils is warranted by (a) the improved prediction of P sorption capacity obtained by adding clay content to Ca_{M3}, and (b) the widespread availability of soil survey information (i.e., series and map unit texture) from which to infer clay content.

As illustrated in Fig. 3, the reference P_{sat} was strongly correlated ($r = 0.84$) with $P_{M3}Ca_{M3}^{-1}$. Inclusion of soil clay content as an added predictor of P sorption capacity did not substantially increase the strength of this correlation ($r = 0.86$),

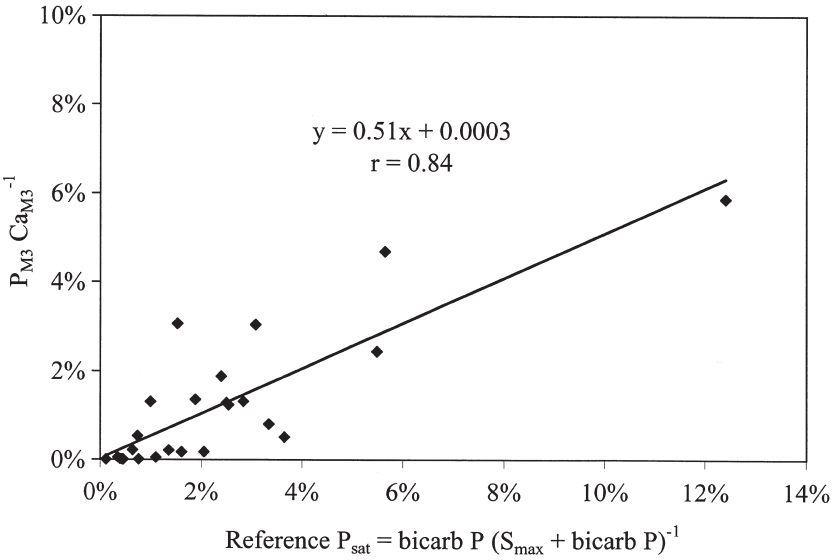

Figure 3. Relationship of reference Psat to P_{sat} estimated from Mehlich-3 data in alkaline soils.

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indicating that improved prediction of P sorption capacity is not as important to P_{sat} estimation in these soils as estimation of sorbed P. The high degree of correlation between the reference P_{sat} and $P_{M3}Ca_{M3}^{-1}$ provides further support that Mehlich-3 may be an appropriate soil test for alkaline soils, despite its poorly buffered, acidic nature. Indeed, this study included a diversity of alkaline soils ranging from weakly alkaline (pH = 7.3) to calcareous (pH = 8.3).

CONCLUSIONS

Soil P sorption saturation is increasingly used as an environmental indicator of soil P availability to runoff, but is generally estimated from data that are not readily available through soil testing laboratories and national databases. In this study we compared established measures of P_{sat} with P_{sat} estimated from Mehlich-3 data. Results show that Mehlich-3 data can be effectively used to estimate P_{sat} for over a wide range of acidic and alkaline soils. Furthermore, in acidic soils, truncated versions of the P_{sat} equation, specifically those excluding Fe from estimation of P sorption capacity, are equally strong in predicting P_{sat} as unabbreviated equations that include Fe. As most soil testing laboratories currently conducting Mehlich-3 extraction employ ICPs, analytes required to estimate P_{sat} (P_{M3}, Al_{M3}, Fe_{M3} and Ca_{M3}) are measured simultaneously. Thus, this study supports the use of readily-available soil testing information in estimating P_{sat}

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